

Membrane Surface with Dimples in Vacuum Membrane Distillation

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Abstract

Objectives: This work presents a study of the effect of membrane surface with dimples on the heat transfer in vacuum membrane distillation (VMD). **Methods/Statistical Analysis:** Polyvinylidene fluoride (PVDF) membrane and distilled water as feed solutions are tested in a laboratory-scale cross-flow flat-sheet membrane module with membrane area of 72.4 cm². A perforated aluminum support embedded in the permeate compartment is used to support the membrane during the VMD process. **Findings:** The results show that the dimples stamped on the membrane surface by the perforated support having the diameter and depth approximately 5 and 1 mm, respectively. The permeability of the membrane with dimples increases by 3 – 20% at the corresponding feed temperature of 75 – 95°C. The deviations between the heat transfer coefficients predicted by a Nusselt correlation with dimpled effect and the experimental values are less than 10%. **Application/Improvements:** These findings are significant to reveal the influence of membrane deformation effect on the heat transfer correlation which is used to predict the VMD flux.

Keywords: Dimpled Surface, Heat Transfer, Perforated Permeate Support, Vacuum Membrane Distillation

1. Introduction

Membrane distillation (MD) is a separation process where vapour is thermally driven through a porous hydrophobic membrane. Feed solution at relatively high temperature is brought into direct contact with one side of the membrane surfaces. Vapour is condensed on the other side of the membrane surface by different ways which categorise the MD into four different configurations: (i) direct contact membrane distillation (DCMD), with the membrane surface in contact with cold water; (ii) air-gap membrane distillation (AGMD), with the membrane surface in contact with stagnant air associated with a cold plate; (iii) sweeping gas membrane distillation (SGMD), with the membrane surface swept by an inert gas; and (iv) vacuum membrane distillation (VMD), with the membrane surface is maintained under vacuum conditions or low pressures.

VMD exhibits the highest flux amongst the abovementioned configuration types because the magnitude of driving force in VMD is the largest. The

membranes that frequently used in VMD are made from polymers^{1,2}. Viscoelastic properties of the membranes can deform when the polymeric membranes are exposed to pressure gradients³. The effects of the membrane deformation have been well studied in pressurised membrane processes, such as reverse osmosis and pressure-retarded osmosis^{4,5}. Membrane deformation occurs during the membrane separation process, especially when there is an apparent pressure gradient applied in the normal direction to flat-sheet membranes and a porous support is in direct contact with the membrane surface in the module.

Although pressure gradient has significantly deformed the membranes and affected the separation performance in other pressurised membrane separation systems, the membrane deformation effect on the VMD performance is still remained unknown. In this study, the effect of membrane deformation on the heat transfer performance of the cross-flow VMD is investigated. A home-made rectangular flat-sheet membrane module and a perforated aluminium support embedded in the

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permeate compartment are used. The experimental data from our previous paper are examined⁶.

2. Materials and Methods

One type of commercial polyvinylidene fluoride (PVDF) flat-sheet membrane (catalogue no.:10413096, Westran S.) with a nominal pore size $0.2 \mu\text{m}$ was supplied by Whatman, Germany. The detailed description of the membrane module design is as follows. The feed flow channel employed in this study is rectangular. The dimensions ($H \times L \times W$) of the feed flow channel employed in this study are $13 \times 102 \times 70 \text{ mm}^3$ resulted in the effective membrane area 72.4 cm^2 . The bottom of the feed flow channel is bounded by the membrane. The membrane is supported by the perforated aluminium support. The thickness of the support is 5 mm. The support comprises of circular holes and porosity about 74% with the diameter of the holes is 5 mm. It is worth noting that the details of the measurement of the membrane permeability and the VMD experiment have been described in our previous publication⁶.

3. Results and Discussion

3.1 Dimpled Membrane Surface

Figure 1 shows the perforated support used in this work and the membrane after VMD operation. Due to the perforated support and vacuum applied on the permeate compartment, dimples are stamped over the membrane surface during the VMD process. It is worth noting that the dimples are permanently formed on the membrane surface. The diameter and depth of the dimples are approximately 5 and 1 mm, respectively.

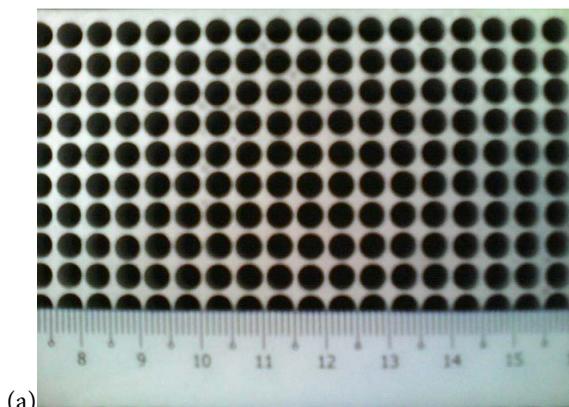


Figure 1. (a) Perforated aluminium support embedded in the permeate compartment which is used to support the membrane during VMD. (b) Dimples stamped over the PVDF membrane surface after the VMD process.

3.2 Membrane Permeability

The low-pressure gas permeation method is used to measure the membrane permeability. The low-pressure type of gas permeation technique is selected because the low range of pressure can preserve the original physical structure of the membranes and a small change on the membrane structure can be sensitively detected. The detailed procedures of the measurement on the membrane permeability are illustrated in our previous publication⁶.

Figure 2 shows the relationship between the N_2 gas flux and pressure differences across the membrane at which after the membrane was subjected VMD flow rate of 600 mL/min and the respective feed temperatures from 75 to 95°C . Interestingly, the membrane permeability is increased when increasing the VMD feed temperature.

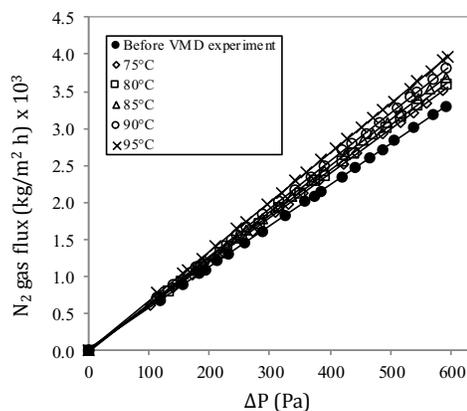


Figure 2. Variation of the membrane permeability after subjected to the VMD process for various feed temperatures under a feed flow rate of 600 mL/min .

The percentages of the membrane permeability enhancement (φ) are calculated as follows:

$$\varphi = \frac{S - S_i}{S_i} \times 100 \quad (1)$$

where S_i and S are the initial slope and current slope of the linear lines as shown in Figure 2. The membrane permeability increases by 3 – 20% at the corresponding feed temperatures range from 75 to 95°C. Figure 3 summaries the membrane permeability enhancement at six feed flow rates. The error bars corresponding to each point are less than 2%. The trends of the graphs show that the effect of the feed temperature on the membrane deformation is greater than that of the feed flow rate.

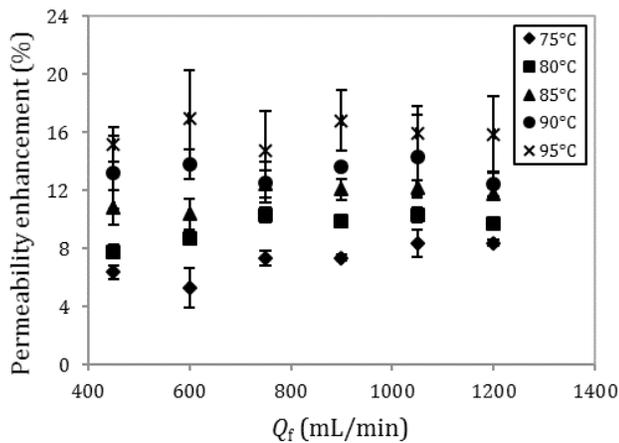


Figure 3. Permeability enhancement of the membrane with dimpled surface.

3.3 Effect of Dimples on Temperature Polarisation

In this work, distilled water is tested as the feed solution. As a result, temperature polarisation effect is considered^{7,8}. A general form of heat transfer correlation for the rectangular cross-flow channel with a porous and phase-change heat transfer wall is stated as follows⁶⁻⁸:

$$Nu = aRe^b Pr^c \quad (2)$$

where Nu , Re and Pr are Nusselt, Reynolds and Prandtl numbers, respectively; a , b and c represent the characteristic constants of the module design and liquid flow regime.

By employing the procedures described in our previous article⁶, a Nusselt correlation by considering the dimpled effect of the membranes is developed. As the

membrane deforms during the VMD process, the average of the initial value and the final value of the membrane permeability is taken into account. The resulting correlation is as follows:

$$Nu = (3.02 \times 10^{-3}) Re^{0.95} Pr^{3.8098} \quad (3)$$

The heat transfer coefficient (h_L) can be calculated from its corresponding Nusselt number:

$$Nu = \frac{h_L d_h}{k_T} \quad (4)$$

where d_h and k_T are the hydraulic diameter and thermal conductivity of the feed solution, respectively.

In order to study the effect of the dimpled membrane surface on the heat transfer performance on the VMD process, the experimental values of the heat transfer coefficients ($h_{L,exp}$) are determined by using iterative method where the un-deformed membrane structures are considered^{6,7}. Figure 4 compares the heat transfer coefficients calculated by using Equations (3 – 4) with the experimental values. The magnitude of the deviations between the calculated and experimental values are less than 10%. This indicates that the membrane surface with dimples do not affect the heat transfer performance in this VMD system significantly.

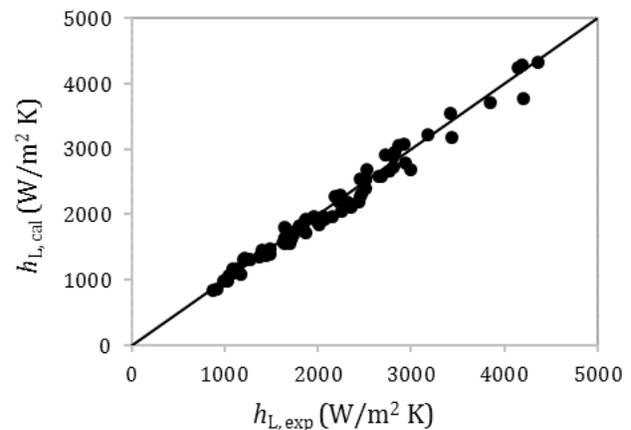


Figure 4. Variation of the membrane permeability after subjected to the VMD process for various feed temperatures under a feed flow rate of 600 mL/min.

4. Conclusion

This works presented an experimental study of VMD processes in a laboratory fabricated cross-flow flat-sheet

membrane module. The commercial PVDF membrane is tested. The perforated aluminium support is embedded in the permeate compartment where vacuum pressure is applied. Due to the pressure difference is essential in VMD, the effect of the membrane deformation is investigated in this work. The findings show that:

1. Dimples are formed over the membrane surface during the VMD process due to the vacuum pressure. The dimples are permanently formed on the membrane surface.
2. The permeability of the membrane with dimples is 3 – 20% higher than that un-deformed membrane.
3. The heat transfer coefficients calculated by using the Nusselt correlation with dimpled effect are approximately 10% deviate from the experimental values which do not take the membrane deformation into account. As a conclusion, the dimpled effect does not affect the heat transfer performance of the VMD process significantly.

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